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13. ABSTRACT *(Maximum 200 words)*

The purpose of this award is to construct a dedicated testbed for the characterization of phase and amplitude modulating properties of spatial light modulators (SLM). The system is specifically a phase shift interferometer configured around a 2000 x 2000 CCD imager to precisely measure the SLM transmittance and diffraction pattern with a resolution in excess of current SLMs. The testbed will be used in current and pending studies. It also has application to a new optical correlation architecture described in a recent patent and journal paper.

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19. SECURITY CLASSIFICATION OF ABSTRACT

20. LIMITATION OF ABSTRACT

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FINAL REPORT

The purpose of this award is to construct a dedicated testbed for the characterization of phase and amplitude modulating properties of the SLM. The system is specifically a phase shift interferometer configured around a 2000 x 2000 CCD imager to precisely measure the SLM transmittance and diffraction pattern with a resolution in excess of current SLMs. The testbed will be used in current and studies awarded since this current award. It also has application to a new optical correlation architecture described in a recent patent and journal paper (cited in publications list below.)

1.0 Progress during award period

All equipment has been ordered and installed with the exception of one custom-made beamsplitter which was returned as it did not meet specifications. The remanufactured part is due to be delivered in early October. After this all accounts will be finalized.

Also during this period R. W. Cohn visited U.S. Army Missile Command for technical discussions on the testbed with Bill Friday and Bob Guenther. This trip was funded by Army Research Office. We presented results on models on the effects of random and systematic phase errors, and identified a case where Micom engineers have concerns about the effects of a combination of systematic and random errors on correlation. Specifically, the programming errors are quantized values of modulation that have a random uncertainty bound. Since this meeting we have extended our models so that they are now able to predict deterioration of correlation performance due to this combined effect. We have since published a paper in SPIE proceedings and it has been submitted to the referreed journal Optical Engineering. We also discussed the possibility of the University of Louisville acquiring a copy of the standalone driver circuit for the TVT6000 liquid crystal television display that they are developing.

I also presented new information to Micom on the optical characteristics of this display and of the driver board in the TVT6000 projector. Some of the variability that Micom has seen in setting the transmittance at individual pixels may be due to the sharpness control on the projector. It causes ringing of the driver board signal which can alter the desired settings over several adjacent pixels. Ringing is much more pronounced in the horizontal direction, and its effect is evident on far-field diffraction patterns of white random input modulation. This is seen as a modulation pattern of vertical stripes on top of the ideally anticipated speckle pattern.

The equipment provided by this grant has already been used in experiments demonstrating the pseudorandom encoding method (publication 3 in sec. 2.2). Two publications that are now being prepared and that will specifically acknowledge ARO support are:

R. W. Cohn and M. Liang, "Experimental Demonstrations of Pseudorandom Phase-only Encoding," to be submtitted to *Applied Optics*.

R. W. Cohn, M. Liang and S. B. Bidiwala, "Random Phase Method for Real-Time Steerable Spot Arrays," to be submitted to *Applied Optics*.

When these and subsequent articles using the equipment from this grant appear in print, reprints of will be forwarded to ARO.

2.0 Related Research of Interest to DoD

Related research projects that will use the testbed are indicated in this section. The performance on these activities will be improved through the use of the testbed. The testbed will allow us to verify predictions in several of the publications cited in the technical communications subsection.

2.1 Related Research Contracts

Awarded

R. W. Cohn, "Speckle Generation by Phase-Only Spatial Light Modulators: Effects of Random Phase Errors and Pseudo-Random Modulation," ARPA (B. Hendrickson) through Rome Laboratory (J. Horner), $137,053. (26 June 1992 to 30 September 1994)

The goal of this program is the development of mathematical models and performing experiments on the diffraction of coherent light from phase-only spatial light modulators in which the phase modulation caused by each pixel is modeled as a random variable. We have found during this program cases (especially vaild for correlators) in which systematic phase errors can also be analyzed using random models. Some recent progress since the Testbed project started has been:

Experimental Characterization of TVT6000. Our objective has been to produce a 2π range of phase modulation with only a small degree of amplitude modulation. This range of modulation is needed to experimentally demonstrate the pseudorandom synthesis procedure. Our ultimate goal is to perform this experiment and compare it to our theory and simulations. We have produced 340° of phase shift with a tandem of two projector panels. Amplitude uniformity of better than $\pm$ 3 % to 8 % was measured for various settings. However the contrast of the amplitude measurement was around 25 % and thus we feel the uniformity measurement may be overly optimistic. We anticipate much more accurate measurments when the testbed comes on line, since phase shift interferometry tends to subtract out and minimize systematic background levels.

Pseudorandom phase-only approximation method described in a recent Applied Optics paper (see sec. 2.2) was prepared as a patent disclosure at the request of the U. S. Air Force and a U. S. patent was filed 27 January 1994 under the title "Method of Producing an Optical Wave with a Predetermined Optical Function."

R. W. Cohn, "Influence of Non-Ideal Spatial Light Modulators on the Performance of Optical Processors," DAAH04-94-G-0358 Advanced Research Projects Agency through Army Research Office (D. Seitz), $137,050. (20 September 1994 - 19 September 1997)

This is an AASERT award that has been budgeted to support two Ph.D. research assistants for three years. Research activities include 1) extending our current models of the effects of systematic and random SLM phase errors, 2) performing optical experiments aimed at confirming and demonstrating the validity of the system models, 3) demonstrating effects of non-ideal performance on optical processor prototypes, and 4) developing measurement procedures for more quickly and precisely characterizing the performance of SLMs and processors. We anticipate that this support will permit us to complete the full automation of the phase shift interferometer in the first year. We estimate the amount of labor to complete this specific task to be one student year.

R. W. Cohn (PI), D. L. Chenoweth, L. G. Hassebrook, K. M. Walsh, "Technology Base in Optical and Opto-electronic Correlators," NCCW-60, National Aeronautics and Space Administration through Western Kentuky University, $375,000. (1 July 1994 - 14 July 1997)

The goal of this research is to develop and validate a system model that reasonably describes the end-to-end performance of a generic optoelectronic correlator. The model will include the effects of 1) the visual environment, 2) non-ideal optoelectronic components, in particular SLMs, 3) optical filter design, 4) adaptive selection of optical filters. Chenoweth is chiefly responsible for imagery models, and Hassebrook is chiefly responsible for filter design and filter selection. Walsh will fabricate phase-only filters which will be used to experimentally verify designs. Cohn is the principal investigator. He will model the effects of non-ideal SLMs and be responsible for overall integration of the end-to-end model. The testbed will be used in the experiments planned for this project. The work is related to the current contract and involves collaborations with R. D. Juday, NASA Johnson; T. H. Chao, NASA JPL; and J. Downie, NASA Ames who all are optical processor researchers.

Pending

A. A. Farag, D. L. Chenoweth, R. W. Cohn, "Laboratory for Computer Vision and Image Processing," National Science Foundation (NSF), $175,191. (Submitted 1 August 1994, 36 months)

Equipment grant for a Silicon Graphics workstation and peripherals. The investigators on this grant are all involved in image and signal processing research. The workstation will be used to process and evaluate large sets of images in memory; e.g. multiple interferograms captured by the large area CCD camera, and large image data sets that describe a manuevering vehicle vehicle viewed from a changing perspective. The system will be interfaced to the data acquisition equipment in my laboratory and thus the workstation also supports longer term goals of integrating optical correlators and other optical processors with high level robotic vision

systems.

2.2 Related Publications and Technical Communications Since Award of Contract

Journal papers

1. R. W. Cohn, "Performance Models of Correlators with Random and Systematic Phase Errors," *Optical Engineering*. (Submitted 21 September 1994)

2. R. W. Cohn and J. L. Horner, "Effects of Systematic Phase Errors on Phase-Only Correlation," *Applied Optics*, 33, 23, 5432-5439. (10 August 1994)

3. R. W. Cohn and M. Liang, "Approximating Fully Complex Spatial Modulation with Pseudo-Random Phase-Only Modulation," *Applied Optics*, 33, 20, 4406-4415. (10 July 1994)

4. M. Liang, "Lateral Inhibition: Inherent Recurrent Processes in Coherent Optical Propagation," *Applied Optics*, 33, 2, 158-161. (10 January 1994)

Proceedings papers

5. R. W. Cohn and J. L. Horner, "Performance Models of Correlators with Random and Systematic Phase Errors," in *Advances in Optical Information Processing VI*, D.R. Pape, ed., *Proc. SPIE* 2240, 270-277. (7 April 1994, Orlando, FL)

6. L. G. Hassebrook, M. E. Lhamon, R. C. Daley, R. W. Cohn, and M. Liang, "Using Pseudorandom Phase-Only Encoding to Approximate Fully Complex Distortion-Invariant Filters," in *Optical Pattern Recognition V*, D.P. Casasent, ed., *Proc. SPIE* 2237, 204-211. (5 April 1994, Orlando, FL)

7. R. W. Cohn and J. L. Horner, "Limited Phase Modulation and its Effect on Phase-Only Correlation," in *Optical Pattern Recognition V*, D.P. Casasent, ed., *Proc. SPIE* 2237, 147-151. (5 April 1994, Orlando, FL)

Talks with abstracts

9. R. W. Cohn and M. Liang, "Approximating of Fully Complex Spatial Modulation with Pseudo-Random Phase-only Modulation," *Symposium on Binary and Diffractive Optics. Optical Society of America Annual Meeting*, Toronto, Canada, Technical Digest 16, ThU2, p. 184. (7 October 1993)

10. M. Liang, "Optical Realization of a Recurrent Neural Network," *Optical Society of America Annual Meeting*, Toronto, Canada, Technical Digest 16, WR2, p.119. (6 October 1993)

11. R. W. Cohn, "Optoelectronic Correlator Architectures Using a Single Spatial Light Modulator," *Symposium on Miniaturization and Packaging of Optical Computing Systems. Optical Society of America Annual Meeting*, Toronto, Canada, Technical Digest 16, MKK5, p.43. (4 October 1993)

Patents

12. R. W. Cohn and M. Liang, "Method of Producing an Optical Wave with a Predetermined Optical Function," U.S. Patent Application. (Pending as of 27 January 1994. Filed by U.S. Air Force)

13. U. S. Patent 5276636, R. W. Cohn, "Method and Apparatus for Adaptive Real-Time Correlation Using Phase-Only Spatial Light Modulator and Interferometric Detection." (4 January 1994)

Seminars

14. R. W. Cohn, "Real-time Multispot Beam Steering with Randomly Phased Arrays," Seminar to Electrical and Computer Engineering Department, Illinois Institute of Technology, Chicago, IL. (7 October 1994)

15. R. W. Cohn, "Real-time Multispot Beam Steering with Randomly Phased Arrays," Seminar to Rome Laboratory Photonics and Optics Division, Griffiss AFB, NY. (16 September 1994)

16. R. W. Cohn, "Real-time Multispot Beam Steering with Randomly Phased Arrays," Seminar to Computer Science and Engineering Ph.D. program, University of Louisville. (25 August 1994)

17. R. W. Cohn, "Speckle Generation by Phase-only SLMs," *Advanced Research Projects Agency Materials Technology Office (ARPA/MTO) Optoelectronics Program Review*, Monteray, CA (17 June 1994)

18. R. W. Cohn, "The Information Superhighway and the Required Optical Interconnection Technologies," Keynote Speaker *ISA IEEE Kentuckiana Technical Symposium and Expo*, Louisville, KY. (25 May 1994)

19. R. W. Cohn, "Phase-Only Spatial Light Modulators: Effects of Phase Errors on Optical Processor Performance," Seminar to Electrical Engineering Department, University of Kentucky, Lexington, KY. (11 May 1994)

20. R. W. Cohn, "Phase-Only Spatial Light Modulators: Effects of Phase Errors on Optical Processor Performance." Physics and Applied Optics Department, Rose-Hulman Institute of Technology, Terre Haute, IN. (8 February 1994)

21. R. W. Cohn, "Phase-Only Spatial Light Modulators: Effects of Phase Errors on Optical Processor Performance." Physics Department, Alabama A&M University, Huntsville, AL. (9 November 1993)

Technical Discussions with Researchers and Agencies

Visits with

Bob Guenther, ARO, at Micom on testbed, performance model and funding opportunities
Bill Friday, U. S. Army Missile Command, on testbed and performance models
John Caulfield, Alabama A&M, on deformable mirrors for beamsteering and shaping
Don Gregory, University of Alabama, Huntsville on SLM based optical correlators
Russell Chipman U. Alabama, Huntsville, on polarization & phase modulation by LCTVs
Robert M. Bunch, Rose-Hulman Institute of Technology, on SLM properties
Laurence Hassebrook, U. Kentucky, on synthetic discriminant filters and filter banks
Henry Stark, Illinois Institute of Technology, on random encoding and convex projection
James Cusak, Rome Laboratory Photonics Center, on common research interests
Barbara Yoon, ARPA, on integration of optical correlators with robotic vision systems
Charles Hester, Teledyne Brown, DGM SLM and random and systematic phase errors

Phone conversations with

Joe Mait, Army Research Lab, on performance models and design of phase-only filters
Joseph Horner, Rome Lab, on SLM performance models & monitoring of ARPA contract
Gerald Wilkins, Wright Avionics Lab, Dayton, on SLM based beam steering and shaping
Robert Feldmann, Wright Avionics Lab, Dayton, SLM based beam steering and shaping
William Miceli, Office of Naval Research, on beam steering and shaping with SLMs
John Lee, Naval Research Laboratory, on performance analyses of optical processors
Brian Hendrickson, ARPA on performance analyses of optical processors
Paul Repak, Rome Laboratory, Griffiss AFB on optical computing BAA
Richard Juday, NASA, on correlators and the newly funded NASA study
Tom Baur, President Meadowlark Optics on 360° phase modulation depth SLMs
William Bleha, VP, Hughes-JVC Corp. on 360° phase modulation depth light valves
Roylnn Serati, Boulder Nonlinear Systems, on 360° phase modulating FLC SLM devices

Additional information on technical communications

Identification of new phase-only SLMs. During this period we have talked to 4 companies that are developing liquid crystal SLMs for phase modulation. Each believes they can produce 2π phase modulation. The Boulder Nonlinear Systems group believes they can also produce frame rates of 10 KHz, however the required developments are by far more challenging and are at least two years away. The companies are willing to provide samples at a cost of around $20,000 and believe the devices will be available in about 1 year.

3.0 List of Technical Contributors to this Report

Robert W. Cohn, Principal Investigator
Minhua Liang, Ph.D., Research Faculty

4.0 Discussion of Costs

The costs in this contract are $ 68,714 funding from ARO and $ 16,047 University matching. These are all budgeted for the purchase of equipment. All funds have been expended except for $2,465. These are encumbered for the purchase of beamsplitters. As one beamsplitter (with a cost of $612) has been returned to be remanufactured (see sec. 1) the funds have yet to be released to the company. The company confirmed on Sept. 26 that the part will be delivered in early October. At this point all expenditures will be finalized.

List of Equipment purchased on grant

Princeton Instruments	TE/CCD-2032K	Cooled CCD camera	$ 40,195.00
B&H Photo	PB6	Nikon 20 mm lens and bellows for microphotography	931.00
TMC	78-659-01	Optical table with legs, shelf and compressor	9,190.00
Padgett		Rigging costs to install table	1,300.00
Alfax	9315CTP-975	Grayscale printer incl. paper	8,618.00
Gateway	Kultra34F	SCSI controller card for printer	222.00
Burleigh	PZ-90 & RC-44	Piezomirror with voltage controller	4,910.00
Hewlett-Packard	HP3245A	Programmable voltage source with GPIB for automating piezomirror	7,359.00
Lambda Res. Optics	NWP 50 & WP10	4 ea. 2" beamsplitters & 10 mm waveplate	2,465.00
Karl Lambrecht	WPMP4 & MGT25	2" mica waveplate & Glan-Thompson polarizer	1,796.85
Thorlabs	CR200-A	Laser intensity stabilizer	1,204.00
New Focus	9081/9082	2 ea. five-axis aligners	1,204.51
Melles Griot		Assorted optics and optomechanics including:	$ 5,475.41
	02MLE015/001	2" zerodur mirror for piezomirror	
	02MLE017/001	2 ea. 4" mirrors for interferometer corners	
	07MAS018	2 gimbal mounts for 4" mirrors	
	07HPR005	Polarization holder for 2" waveplate	
	07HPR001	2 ea. pol. holder for GT polarizer & 10 mm waveplate	
	07PCH015	6 ea. adjustable height post holders	
	07TTA003	3 ea. prism tables for 2" beamsplitters	

The total charged or encumbered is $84,870.77 which exceeds the budgeted amount of $84,761 by $109.77. The University will cover the $109.77 as additional matching.